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Sexing the Cranium from the Foramen Magnum Using Discriminant Analysis in a Brazilian Sample

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In the identification process, the foramen magnum has shown controversial results in sex estimation. The present study aimed to analyze the morphometric variables of the foramen magnum in Brazilian adult cranium for sex estimation. The sample was composed of 100 craniums (53 males and 47 females) from the documented collection of the Institute of Teaching and Research in Forensic Sciences. The protocol measurement was constituted of two linear measurements: maximum length of the foramen magnum and maximum breadth of the foramen magnum and two formulas to calculate the area, method one (M1) and method two (M2). Descriptive statistics showed statistically significant differences between sex ($p<0.05$) for all variables. The univariate discriminant functions showed an accuracy between 56.0-62.0%, and the multivariate analysis showed a percentage of accuracy between 60.0-65.0%, the greatest accuracy was found combining the two linear measurements with M1(71.7%), even after cross-validation (66%). Receiver Operating Characteristic (ROC) curve analysis showed that M2 is the best parameter for estimating sex (AUC=0.693). A reference table for Brazilians using the foramen magnum parameters was developed based on the results of the ROC curve analysis. In conclusion, the foramen magnum should be used with caution to estimate sex in forensic cases of fragmentary craniums, due to the limited accuracy.

Key Words: forensic sciences, forensic anthropology, foramen magnum, cranium, discriminant analysis, ROC curve, sex determination by skeleton.

Introduction

The basic precept of the science of forensic anthropology is to aid in the identification of human remains (1). The biological profile is the main result of a forensic anthropological examination. Several techniques are employed to achieve a common denominator, the construction of a biological profile that corroborates with a positive identification (1-3). Among the techniques described in the literature, the craniometry, which aims to use measurements of the human cranium in a systematic and universal way, enabling a comparative evaluation between studies carried out in different populations around the world, can be highlighted (4).

Craniometry aims to complement visually assessed traits, correcting the subjective aspect of the personal observations of the examiner. In short, craniometry allows the knowledge of the morphometric variabilities of human craniums, within the natural demands of scientific objectivity (5). The validation of quantitative methodology in the diverse populations around the world is of paramount importance for the global development of forensic anthropology, since the discriminant or regression formulas are sensitive to population variations, which may mean that methodologies developed and validated in a specific population may not be valid for application in another population (6-8). The use of quantitative methodologies is becoming more frequent due to the objectivity of the analysis and the increased methodological reproducibility (6,7,9,10).

The first step in the design of the biological profile is the estimation of sex, as the sex of an individual is one of the main biological indicators of identity (11). Thus, craniometric analysis is considered a tool of great importance in all phases of anthropological examination. The applicability of craniometry for determining the sex of a cranium is only feasible in adults, with the development of secondary sexual characteristics (12). In the adult cranium, sexual dimorphism is inherent in the fragility of the female musculature, which results in a lesser development of the skeletal structures (13).

In view of the anatomical structures that make up the human cranium, the literature has observed that the base of the cranium is one of the structures with a greater chance of prevailing intact despite time and environmental factors (14-17). The diagnosis of sex in intact craniums does not pose a challenge to the examiner, but in cases of fragmented craniums, the estimation of this parameter becomes increasingly difficult (17). For this, the development of methodologies that are applicable to fragmented craniums is of paramount importance for the advancement of forensic anthropology. In this context, studies (6,9,10) have shown that several anatomical regions can be used, and some of them are more accurate than others in sex estimation. Among these structures, the use of linear measurements and circumference area of the foramen magnum (15-23) are emphasized. The foramen magnum is an orifice in the occipital bone, located between the basilar part and the occipital scales, that carries the passage of the brainstem, spinal cord, accessory nerve and vertebral artery. It can be observed in the inferior view of the cranium (24).

In Brazil, few studies have been concerned with the characteristics of the national population. The miscegenation of the Brazilian population due to the intense migration process poses a challenge to forensic anthropologists, since morphometric parameters from other countries may not be valid for the national population (25). The present study aims to analyze the morphometric variables of the foramen magnum in Brazilian adult craniums for sex estimation, assessing its feasibility and reliability for the use in forensic situations.

Material and Methods

The total sample was comprised of 100 Brazilian adults' craniums (53 males and 47 females) with an average age was 57.03 years, with a minimum of 18 and a maximum of 104 (Table 1). The craniums are from the osteological documented collection of the Institute of Teaching and Research in Forensic Sciences (IEPCF). The craniums were exhumed from the Necrópolis Campo Santo cemetery, a public cemetery located in the city of Guarulhos, SP, Brazil. The sex was obtained from the cemetery records. The IEPCF collection is considered a contemporary collection once all the craniums coming out of the 20th century.

The adopted inclusion criteria were: absence of fractures in the foramen magnum area and skulls belonging to individuals older than 18 years. Exclusion criteria were trauma, bone pathologies and extensive fractures.

The protocol measurement of the present study was constituted of two linear measurement and two formulas to calculated the area of the circle based on past publications (22,26). The 2 linear variables used in this study are included in Figure 1): maximum length of the foramen magnum (LFM): linear distance from basion (ba) to opisthion (o); maximum breadth of the foramen magnum (BFM): distance between the lateral margins of the foramen magnum at the point of greatest lateral curvature.

Table 1. Sample age: descriptive statistics

Sex	n	Mean	SD	Median	Minimum	Maximum
Male ♂	53	54.15	18.95	56	18	97
Female ♀	47	60.28	18.89	61	20	104
Total♂♀	100	57.03	19.07	57.5	18	104

The measures were performed directly on the craniums, using a Digital Caliper (Lee Tools, Houston, TX, USA) with an error margin of 0.01 mm. All variables were recorded in mm with two decimal places. The interobserver and intraobserver agreement was performed by two observers in 20 skulls. The protocols were applied independently, at different times, and with a one-month interval between measurements; these skulls were not part of the final sample.

According to previous studies, the shape of the foramen magnum resembles a geometric circle (22,26). As a result, the LFM and BFM can be used to calculate the area of the circle. In the present study, two formulas were used to calculate the area. The first formula (M1), which is based on the same variables measured in the present study, with LFM being the height (h) and BFM being the width (W), was published by Teixeira (22): $\text{Area} = \pi \times ((h \times W)/4)^2$

The second method (M2) was described by Routal (26), utilizing the same measurements as described above: $\text{Area} = \frac{1}{4} \times \pi \times W \times h$

The data were tabulated, and a descriptive analysis and independent t test were performed to verify the differences between the groups (male and female). Univariate and multivariate discriminant analysis was used to study the sexual dimorphism of the sample. The discriminant function was created for each variable analyzed for each sex as follows: P= a + b1*x1 + b2*x2 a2 + … + bm*xm, where a is a

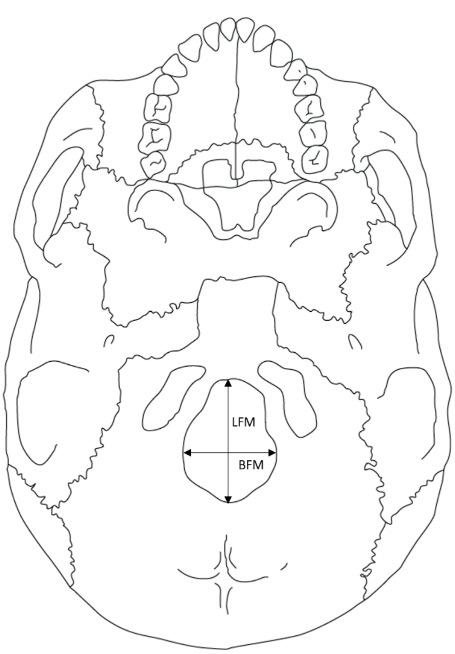

Figure 1. Foramen magnum measurements: vertical arrow LFM and horizontal arrow BFM.

constant, b1 through bm are the discriminating coefficients, and x1 through xm are discriminating variables (17). To estimate the sex, the values of measurements must be included in the equation for male and female. The greatest product of P indicates the sex. The sectioning point for discriminant analysis were calculated using the mean of the female and male centroid group scores(17). Cross-validation was applied to compensate for the percentage of misclassified observations. The receiver operating characteristic (ROC) curves were used to develop a reference table of the Brazilian population using foramen magnum parameters. The percentages of correct classifications in the table were 75%, 80%, 85%, and 90%, and the sectioning point was calculated using the mean of the medium values of the sexes (27). All tests were performed at a significance level of 5%, the univariate and multivariate analyses were performed using the STATA 12.0 and the ROC curve analyses were carried out using MedCalc.

Results

The interobserver analysis demonstrated a moderate correlation (LFM=0.59 and BFM=0.55). The intraobserver also showed moderate correlation for both variables but lower results (LFM=0.41 and BFM=0.40) (28).

The two methodologies of area calculation were compared, and statistically significant differences were found between the two formulas ($p<0.001$). The results of the descriptive statistics showed statistically significant differences ($p<0.05$) for all variables analyzed between sex. All means were greater for males compared to female means (Table 2).

The univariate discriminant functions showed an accuracy that varied between 56.0 and 62.0% (Table 3), and the multivariate analysis showed a percentage of accuracy between 60.0 and 65.0% (Table 3). The variable that demonstrated the greater percentage of accuracy was the M1 (62.0%) followed by M2 (61.0%). The association of LFM, BFM, and M1 showed the best result (65.0%) in multivariate analysis.

The constants and variable coefficients necessary to construct the discriminant functions are shown in Table 3. For example, using the discriminant equations of the LFM and BFM, for an unknown adult cranium with the following measurements, LFM=33.22 mm and BFM=36.29, the functions would be:

Male=-114.84 + (3.48*33.22) + (3.439*36.29) = 125.56

Female= -104.3 + (3.312*33.22) + (3.275*36.29) = 124.57

The products of the functions show that this unknown cranium is most likely to be male (64.2%). The cross-validation analysis showed the same mean correct prediction values of the discriminant analysis for all univariate analysis and the associations of LFM + BFM (62%) and BFM + M2 (60%). For all other multivariate analyses, the cross-validation demonstrated reduced accuracy percentages.

The ROC curve analysis (Table 4) showed that M2 is the best parameter to estimate sex (AUC=0.693), followed by M1 (AUC=0.691), BFM (AUC=0.633) and LFM (AUC=0.627) (Fig. 2). A reference table was developed for the Brazilian population using the foramen magnum parameters based on the results of the ROC curve analysis (Table 5).

Discussion

The cranial base has been found to be the part of the cranium that is most likely to remain intact after the action of time and the environment (14,16,17). The measurement of the foramen magnum to aid in the diagnosis of sex has been studied around the world, and the results have been controversial. Galdames (19), using the anteroposterior and transverse diameter of the foramen magnum in a Brazilian sample, concluded that these parameters should be used

Table 2. Descriptive statistics of the Brazilian sample measurements

Variable*	n	Mean	SD	Median	Minimum	Maximum	Variance	95% CI		p-value
LFM ♂	53	32.36	3.26	32.28	26.24	41.31	10.67	31.46	33.26	0.02
LFM ♀	47	30.79	3.3	30.62	25.30	39.53	10.89	29.82	31.76	
BFM ♂	53	33.7	3.62	34.05	25.12	41.75	13.13	32.70	34.70	0.02
BFM ♀	47	32.09	3.04	32.41	25.23	37.99	9.26	31.20	32.99	
Method 1 ♂	53	861.41	128.75	850.64	680.25	1256.64	16577.60	825.93	896.90	<0.001
Method 1 ♀	47	779.41	95.66	765.52	628.35	1027.80	9151.67	751.33	807.50	
Method 2 ♂	53	856.32	129.2	841.51	671.39	1255.29	16692.80	820.71	891.93	<0.001
Method 2 ♀	47	774.15	96.03	754.65	623.81	1025.21	9222.34	745.95	802.35	

LFM: maximum length of the foramen magnum; BFM: maximum breadth of the foramen magnum with caution due to the lower accuracy and should be implemented with qualitative analyses of the occipital bone. Gapert (17) concluded that in the analyzed sample, the area of the foramen magnum should be considered useful in determining the sex of the cranium.

In this study, all measurements analyzed demonstrated

Table 3. Univariate and multivariate discriminant analysis and cross-validation for manual measurements of the Brazilian sample

Variable*	Unstandandardized Coefficient	Fisher Coefficient ♂	Fisher Coefficient ♀	Group Centroid ♂	Group Centroid ♀	Sectioning Point	λ Wilks	Correct Prediction % ♂	Correct Prediction after cross-validation% ♂	Correct Prediction % ♀	Correct Prediction after cross-validation% ♀	Mean Correct Prediction %	Mean Correct Prediction after cross-validation%
Univariate													
LFM	0.305	3.002	2.857	0.225	-0.253	-0.014	0.945	66.0	66.0	51.1	51.1	59.0	59.0
Constant	-9.633	-49.275	-44.678										
BFM	0.297	2.978	2.836	0.224	-0.253	-0.0145	0.945	66.0	66.0	44.7	44.7	56.0	56.0
Constant	-9.794	-50.875	-46.213										
Method 1	0.009	0.066	0.06	0.337	-0.38	-0.0215	0.885	64.2	64.2	59.6	59.6	62.0	62.0
Constant	-7.192	-29.033	-23.894										
Method 2	0.009	0.065	0.059	0.336	-0.379	-0.0215	0.885	64.2	64.2	57.4	57.4	61.0	61.0
Constant	-7.121	-28.498	-23.418										
Multivariate													
LFM	0.232	3.48	3.312	0.341	-0.385	-0.022	0.882	64.2	64.2	59.6	59.6	62.0	62.0
BFM	0.226	3.439	3.275										
Constant	-14.775	-114.89	-104.3										
LFM	0.009	0.017	0.011	0.337	-0.38	-0.0215	0.884	64.2	62.3	59.6	59.6	62.0	61.0
Method 1	0.01	2.615	2.608										
Constant	-7.35	-50.393	-45.14										
BFM	0.009	0.014	0.007	0.337	-0.38	-0.0215	0.885	64.2	62.3	59.6	59.6	62.0	61.0
Method 1	0.000	2.669	2.669										
Constant	-7.199	-51.557	-46.414										
LFM	0.008	2.648	2.642	0.336	-0.379	-0.0215	0.885	64.2	60.4	57.4	57.4	61.0	59.0
Method 2	0.009	0.016	0.009										
Constant	-7.253	-50.189	-45.014										

BFM	0.009	0.013	0.007	0.336	-0.379	-0.0215	0.885	62.3	62.3	57.4	57.4	60.0	60.0
Method 2	0.004	2.682	2.679										
Constant	-7.184	-51.52	-46.395										
LFM	1.018	544.087	543.333	0.348	-0.392	-0.022	0.878	71.7	66.0	57.4	57.4	65.0	62.0
BFM	1.008	540.939	540.193										
Method 1	-0.03	-20.621	-20.599										
Constant	-40.586	-9038.531	-9008.5										
LFM	0.812	378.273	377.674	0.347	-0.391	-0.022	0.879	67.9	67.9	59.6	53.2	64.0	61.0
BFM	0.797	371.982	371.39										
Method 2	-0.022	-14.176	-14.159										
Constant	-33.878	-6320.428	-6295.468										

*LFM: maximum length of the foramen magnum; BFM: maximum breadth of the foramen magnum

greater means in males compared to females and statistically significant differences between male and female craniums. These results are in agreement with those reported in recent studies (16-20).

The area calculated by Teixeira's formula (M1) showed the higher percentage of accuracy (62.0%; λ=0.885) in the univariate discriminant analysis followed by the M2 (61.0%; λ=0.885). The multivariate analysis demonstrated the best result for the association of the LFM, BFM, and M1, with a percentage of accuracy of 65.0% (λ=0.878). The results of the present study revealed that the association of parameters does not increase the accuracy degree. Gapert (17) demonstrated a higher percentage of accuracy for the association of the maximum length and width (70.3%) compared with the univariate analysis maximum width (65.8%) and length (64.6%). The percentage of accuracy found in the present study using univariate and multivariate analyses are in agreement with the recent literature (15,16,18,21,23). It is important to highlight that the Wilks lambda (λ) showed the low discriminating power of the variables analyzed in the present study, and it had improved as more variables increment the discriminant model, once the Wilks lambda scale ranges from 0 to 1, where 0 means total discrimination, and 1 means no discrimination.

The ROC curve analysis showed similar results to those of the discriminant analysis. M2 showed a better probability of discriminating sex compared to M1. In a recent study on sex estimation using the foramen magnum parameters in craniums from the coastal Karnataka region of India, Babu et al. (18) described higher results than those reported in the present study that could be explained analyzing several factors: the differences in the population groups, the reproducibility of methodology, and a variance in statistical analysis. The foramen magnum length showed an area under the curve of 0.865 and 0.822 for the Teixeira Area. The foramen magnum breadth (AUC=0.654) presented results like those of the present study.

Sex is a discrete dichotomous variable (male and female). Therefore, the probability of correctly estimating the sex at random is 50%. The percentages achieved in the present using the foramen magnum to estimate sex were 14.6% higher than those yielded at random, which demonstrates the gracile of the methodology and the necessity to complement with other qualitative or quantitative parameters.

The reference table was developed to provide a new tool to optimize the process of construction of the biological profile. Due to the small sample analyzed in the present study, the discriminant functions and the reference table should be validated in a large sample of Brazilian individuals. Brazil is the fifth largest country in the world, having a wide range of climate and environmental variation. Additionally, it is the world´s fifth most populous country, and the intense migratory process that makes up the Brazilian demography helped to construct a heterogeneous population with a diverse ethnographic profile (25,29). The discriminant functions and the reference table developed in this study should be used in other nationalities with caution due to the craniometric variations. The validation of these tools is recommended before application in forensic cases. The present study was developed using craniums from a modern collection (20th century), which is important to reduce the secular changes bias. The sex, age, and origin of the craniums that compound the sample of the present study are known, as these craniums are from a public cemetery that provided the obituary of these individuals to develop the records of this collection. The methodologies applied in forensic cases should be developed only in documented samples to reduce the methodological and social bias (17).

In conclusion, the foramen magnum should be used with caution to estimate sex in forensic cases of fragmentary craniums, due to the limited accuracy of this methodology. The application of these measurements should be complemented with other qualitative and/or quantitative parameters to

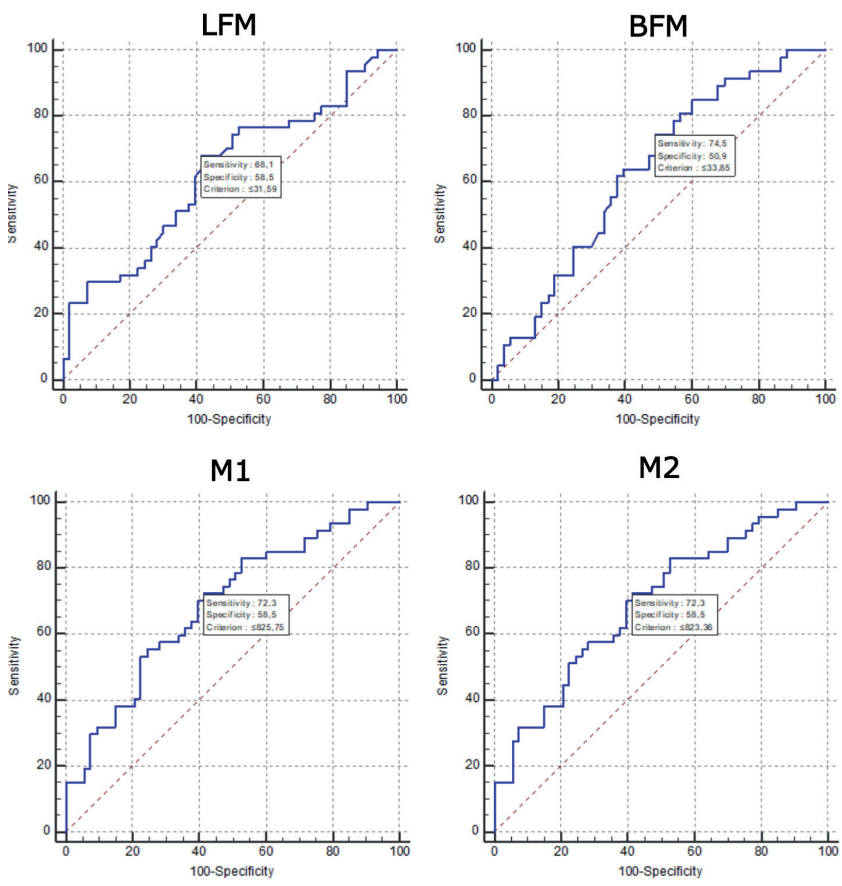

Figure 2. ROC curve graphs and sectioning points.

Table 4. ROC curve analysis for manual measurements of the Brazilian sample.

Variable*	AUC	*p* value	Lower Limit	Upper Limit	Sectioning			Male (%)	Female (%)
LFM	0.627	<0.05	0.524	0.721	♀≤	31.59	≥♂	68.1	58.5
BFM	0.633	<0.05	0.531	0.727	♀≤	33.85	≥♂	74.5	50.9
Method 1	0.691	<0.05	0.756	0.921	♀≤	825.75	≥♂	72.3	58.5
Method 2	0.693	<0.05	0.593	0.781	♀≤	823.36	≥♂	72.3	58.5

*LFM: maximum length of the foramen magnum; BFM: maximum breadth of the foramen magnum

Table 5. Reference table for manual measurements of the Brazilian population

Variable	Male				Sectioning Point	Female			
	95%	90%	80%	70%		70%	80%	90%	95%
LFM	35.83	35.31	34.17	32.28	31.57	30.13	29.2	28.26	27.56
BFM	37.13	35.73	34.73	33.77	32.89	31.79	30.61	28.43	27.29
Teixeira Area	968.17	901.26	857.89	822.45	820.41	787	745.3	710.63	686.97
Routal Area	946.84	913.24	855.06	820.91	815.23	783.22	736.67	705.63	696.7

increase the percentage of correct classifications. In cases of complete craniums, the application of methods with higher accuracy are recommended.

Resumo

No processo de identificação humana, a análise do forame magno apresenta resultados controversos para estimativa do sexo. O presente estudo teve como objetivo analisar as variáveis morfométricas do forame magno em crânios adultos brasileiros para estimação sexual. A amostra foi composta por 100 crânios (53 sexos masculino e 47 sexo feminino) pertencentes a coleção osteológica documentada do Instituto de Ensino e Pesquisa em Ciências Forenses. A medida do protocolo foi constituída por duas medidas lineares: comprimento máximo do forame magno e largura máxima do forame magno e duas fórmulas para calcular a área, método um (M1) e método dois (M2). As estatísticas descritivas evidenciaram diferenças estatisticamente significativas (p<0,05) para todas as variáveis. As funções discriminantes univariadas apresentaram uma porcentagem de acerto entre 56,0-62,0% e a análise multivariada mostrou uma porcentagem de acerto entre 60,0-65,0%. A análise da curva ROC apontou que M2 é o melhor parâmetro para estimar o sexo (AUC=0,693). Uma tabela de referência para brasileiros que utilizam os parâmetros do forame magnum foi desenvolvida com base nos resultados da análise da curva ROC. Em conclusão, o foram e magnum deve ser usado com precaução para estimar o sexo em casos forenses de cranio fragmentado, devido à precisão limitada.

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